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Investigation of the Real-Time Accuracy of the DGPS Method

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13. ABSTRACT *(Maximum 200 words)*

The Real-Time Differential GPS (DGPS) method using the C/A code (not carrier) has the potential to provide positional accuracy to 1-3 meters (1σ). DGPS is a viable option for positioning tasks in hydrographic surveying. Determination of the real-time DGPS accuracy is the main objective of this study. Accuracy provided by DGPS may deteriorate depending upon operational conditions. Factors influencing DGPS accuracy are discussed. Background of the DGPS method is given including mathematical description, but emphasis is on general concepts and discussion of DGPS error sources. DGPS implementation problems are discussed. Specific real-time data links and their throughput are analyzed. The RTCM-104 standard for meter level DGPS applications and the different DGPS systems used in the study are discussed. The analysis is performed using real-time and post-processed DGPS results. The influence of two major factors affecting the DGPS accuracy: distance from the monitor station and data rate of differential corrections; is investigated. The role of the data rate is evaluated using simulated data rate scenarios. Particular attention is given to the impact of Selective Availability (SA) on meter level DGPS performance during specific days of heavy SA.

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PREFACE

This report was funded by the Civil Works Surveying and Mapping Research and Development Program, Work Unit 32790 "Meter Level DGPS" for which Ms. Sally L. Frodge is the Principal Investigator.

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ADDENDUM TO THE REPORT "INVESTIGATION OF THE REAL-TIME ACCURACY OF THE DGPS METHOD"

The DGPS accuracy analysis was carried out using the GPS receivers that were available at the end of 1991. These receivers were single frequency C/A code receivers with C/A code noise of about 1 m. However we have witnessed the rapid growth of the civilian receiver technology in 1992 with the introduction of such receivers like Wild SR299 (Magnavox) , NovAtel, Trimble 4000 SSE and Turbo Rogue. These receivers have one or two of the two unique features:

- improved 30-40 cm C/A code noise
- cross-correlated Y-code data enabling derivation of L2 range measurement without tracking P-code

The C/A code noise improvement is remarkable. The code noise is the major error source of the real-time DGPS for short distances (less than 50 km) using a high speed data link. Therefore the C/A code noise improvement by a factor of 2 obtained with the new receivers transfers to the same position accuracy improvement. It effectively enables horizontal positioning with accuracy below 1 meter.

The second feature offers capability to virtually eliminate ionospheric errors in DGPS positioning. This capability is important for operations at long distances from the reference stations (greater than 100 km) or operations in high latitudes(greater than 50 degrees). However one should notice that present RTCM-SC 104 Version 2.0 cannot take advantage of this feature because the ionospheric effects are not removed from pseudorange corrections. The new RTCM-SC 104 Version 2.1 (directed at kinematic applications) provides necessary space for L2 range data. The by-side effect is the increasing the amount of transmitted data from the monitor station that leads to the increasing the delay of the received data. Therefore some additional research on the most optimal way of using L2 range data in real-time DGPS positioning is needed.

I) INTRODUCTION AND OUTLINE OF THE STUDY

The Real Time Differential GPS (DGPS) method has the potential to provide positional accuracy to 1-3 meters (1σ). It is a viable option for various positioning tasks in hydrographic surveying. However, the DGPS accuracy may deteriorate depending upon operational conditions. Determination of the real-time DGPS accuracy is the main objective of this study. The second objective is an investigation of the influence of different factors that affect meter level DGPS accuracy.

The theoretical background of the DGPS method is given in the first part of this report. In the mathematical description, emphasis is put on general concepts and on the discussion of the DGPS error sources. The DGPS implementation problems are discussed next. Specific real-time data links and their throughput are analyzed. The limitations of the RTCM-104 standard for meter level DGPS applications are addressed. Different DGPS systems used in the study are briefly described.

The analysis is performed using real-time and post-processed DGPS results. The influence of two major factors affecting the DGPS accuracy: distance from the monitor station and data rate of differential corrections; is investigated. The role of data rate is evaluated using simulated data rate scenarios. Particular attention is given to the impact of Selective Availability (SA) on meter level DGPS performance during specific days of heavy SA.

II) DGPS METHOD - BACKGROUND

The Differential GPS method is used to compensate for some errors in the stand-alone GPS position solution whether natural or deliberately induced. An example of natural errors are tropospheric and ionospheric errors. The induced errors are Selective Availability (SA) clock dithering and orbit errors. The basic principle of the method is to use at least one reference station at a known location to determine the errors in GPS observations and to apply this information in the user solution at the second station.

The error e_A at reference station A, estimated by the pseudorange correction, is computed by stripping off from measured pseudorange, the true range, receiver and satellite clock offsets

$$e_A = p_A - (cdT_A + cdt + d_A) \tag{1}$$

where:

e_A - pseudorange correction
p_A - measured pseudorange
c - velocity of light
dT_A - receiver clock offset

dt - satellite clock offset
d_A - true range between receiver and satellite.

A fundamental assumption of the DGPS method is the equivalence (strong correlation) of errors at reference station A and remote station B,

$$e_A = e_B \tag{2}$$

Therefore, the determined error e_A at reference station A is applied to the simultaneously measured pseudorange at user station B to provide true range d_B biased only by the receiver clock offset

$$p_B - e_A - cdt = d_B + cdT_B \tag{3}$$

The right hand side of equation (3) contains two terms that are functions of unknown parameters. The range d_B is a well known function of the unknown coordinates of point B. The second term is receiver clock offset at point B scaled to distance units. These unknown parameters are solved for using estimation techniques like least-squares or Kalman filtering. At least four simultaneous differentially-corrected pseudorange observations are required to obtain a three dimensional solution.

Note that all parameters in equations (1) to (3) are referenced to the same instant of time. In real-time DGPS, error information is transmitted to the user by means of some data link which has certain transmission latency and a limited data rate. Because of this latency the received pseudorange correction refers to the past time at instant t_0. Therefore the user has to apply at present time t_i predicted error based on earlier computations. It is computed by,

$$e_i = e_0 + \dot{e}\,(t_i - t_0) \tag{4}$$

where:

t_i - present time instant
e_i - predicted pseudorange correction at t_i
t_0 - pseudorange correction reference time
e_0 - computed pseudorange correction at t_0
$\dot{e}$ - pseudorange correction rate

Equations (1) through (4) express in a concise way the principles of real time DGPS. Note an implicit assumption of the method - equivalence of errors at reference and user stations at the same instants of time. Thus, an application of equations (1) and (3) results in cancellation of the common errors in the user solution. This is a fundamental principle of differential positioning.

To complete this discussion, consider the implication of a case when raw observations

from monitor and user stations are available simultaneously. This case relates to post-processing or to real-time operation when data link with sufficiently high throughput (data rate) is available. Equation (3) can be developed to bypass error computation by substituting error e_A from (1) directly to equation (3) in a form

$$p_B - p_A = c(dT_B - dT_A) + (d_B - d_A) \tag{5}$$

The equation (5) shows clearly the advantage of having time matched observations from both monitor and user stations. In this case, any residual error associated with the satellite clock offset is canceled. This is due to the fact that satellite clock offset is the same for two receivers observing at the same time. The right-hand side of equation (5) contains the geometric term and the difference of clock offsets at both stations. The clock offset difference can be solved for together with the unknown user point coordinates.

The equations (1) to (4) and equation (5) describe two equivalent approaches to the differential method. In general, equations (1) to (4) are more suitable for real time DGPS while equation (5) is for postprocessing. However, the specific case of using equation (5) for real-time application will be briefly presented in the description of the DGPS systems used in the study.

III) DGPS ERROR ANALYSIS

DGPS accuracy is limited by factors including receiver noise, non-equivalence of user true error and pseudorange correction. The receiver noise can be reduced with carrier phase smoothing, but multipath can be a significant error source. The multipath error on range can reach tens of meters on C/A code with periods of several minutes. The static-reference station is somewhat more prone to the effects of multipath than dynamic-user station. In a dynamic case, multipath does not have quasi-random behavior as in a static case because of receiver movement. Moreover, in hydrographic applications there is less multipath from water. In general, the influence of multipath can be reduced by careful antenna location and by raising the elevation mask to 10 or 15 degrees.

The second factor is the difference of pseudorange correction and user true error. It results in the presence of systematic residual errors in DGPS positioning. The fundamental assumption of equation (2) is, in reality, not valid. This is the main topic of the investigation.

A pseudorange correction, e_A computed according to equation (1) expresses composite GPS range error. It is now decomposed into specific terms, switching from subscripts to superscripts for clarity;

$$e_A = d_d^A + d_{ion}^A + d_{trop}^A + \delta t \tag{6}$$

where:

d_d - orbit error
d_{ion} - ionospheric delay
d_{trop} - tropospheric delay
δt - residual satellite clock error

The first three terms are varying slowly with time while the last one is fast changing. Assuming that the errors are not time matched, the residual differential error at user station B can be expressed as the difference of pseudorange corrections e_B at point B and e_A at point A

$$e^B = e_B - e_A \tag{7}$$

Substituting to equation (7), equation (6) and the same equation developed for point B, the residual differential error is expressed by

$$e^B = (d_d^B - d_d^A) + (d_{ion}^B - d_{ion}^A) + (d_{trop}^B - d_{trop}^A) + \delta(t) - \delta(t_o) \tag{8}$$

The error terms in equation (6) have different behavior. The first three terms are distance dependent - spatially correlated, while the last one is time dependent - temporally correlated. If Selective Availability were off, the last term would be negligible due to the high stability of GPS satellites clocks.

Spatially correlated errors map into user position errors in the same way. A simple yet useful empirical formula can be used for assessing the size of the position error, namely

$$dr = \frac{e}{hd} \tag{9}$$

where:

dr - position error
e - specific spatial error
d - distance between reference and monitor station
h - GPS satellite height 20,000 km.

Formula (9) suggests that the influence of spatially correlated errors on user position is negligible for distances below 100 km. Over this range (greater than 100 km) the error contribution starts to be a factor for DGPS target position accuracy below 3 meters. This statement is further demonstrated with real data in section VII. In this case the only way to improve the accuracy is to reduce the size of the absolute and hence residual differential individual errors. While orbit error is assumed to be fixed, influence of tropospheric and ionospheric delays can be done by simple modelling.

The ionospheric model transmitted in the GPS message can be used by a C/A code user to partially remove an effect of ionosphere. Although the ionospheric model is believed to be accurate to only 50%, applying it reduces residual DGPS error by 50% without any cost. The existing tropospheric correction models like Hopfield and Sastamoinen, that are believed to be accurate to 95% in normal conditions, can be used to estimate a differential tropospheric correction. Standard atmosphere parameters suffice to represent actual meteorological parameters in most cases. Introducing differential tropospheric and ionospheric corrections reduces the size of DGPS error for the distances greater than 100 km. This approach has been taken in development of DGPS systems that go beyond the RTCM SC-104 standard.

Selective Availability (SA) is another factor that affects the accuracy of DGPS. It influences both orbit and satellite clock errors. The contribution of SA to orbit error is typically below 100 meters, 95% of the time. The SA satellite clock dithering produces the error in predicted pseudorange correction, computed according to equation (4) because of non-linear characteristics of clock dithering. The greater the prediction interval ($t-t_0$), the greater the error. The prediction interval is proportional to the update rate of differential corrections. Therefore, the higher the correction update rate the better the DGPS position.

Summarizing the error analysis, there are two factors that affect DGPS accuracy the most: station separation and update rate of differential corrections. The analysis of their influence is the main part of this investigation.

IV) DATA LINK VERSUS AGE OF CORRECTION

The age of the received RTCM SC-104 correction or raw data packet is an important factor that affects DGPS accuracy. The higher the data rate or throughput, the better the cancellation of SA effects. The throughput level is directly related to the type of data link used. Different data links have operational as well as cost issues that need to be considered for the application. A thorough study of different data links is given in (Lanigan et al,1990). Therefore only certain practical implementation problems are addressed as well as possible RTCM SC-104 throughput improvements are discussed.

There are three common data links that are currently being used by DGPS operators. They are as follows:

The UHF data link (300 - 3000 MHz range but typically 420 - 480 MHz) is a "line of sight" system and works very well for local setups. High throughput is possible. Reliable range generally is less than 20 km.

The HF system (3 - 30 Mhz but typically 4 - 7 MHz) is a skywave system capable of long range, 350 km or better but with low throughput. Licensing is a problem in the HF frequency band. Often two different frequencies are used to assure that you will receive the data from at least one monitor station (or one of the co-located stations).

Satellite data link via geostationary telecommunication satellites is a viable alternative for long range operations eg. offshore. Data rates vary from 300 to 1200 baud. Operational limitations

of this data link are size of the antenna and cost of satellite services.

Table 1 shows what correction age (AOC) can be expected for different data link types shipping standard RTCM-104 (version 2) format differential data. The AOC includes the time it takes to handle handshaking or signalling requirements that radio and satellite systems may require plus the actual time it takes to transmit the data over the distance.

Data links	Baud rate (bps)	AOC (sec)
UHF	9600	.5
HF	300	3.2
STARFIX	600	2.0

Table 1
Age of Corrections versus Data Rate

Handshaking or signalling requirements are varied depending on the radio/satellite equipment used, the manufacturer, and the options selected by the user. The delay in sending the data over the selected link can vary greatly depending on what options are available and how the user selects them.

Example 1:
Many radio link systems transmit an "acknowledgement" signal from the receive side of the radio link back to the transmitting side to tell the transmitter that the data transmission process has been successful. After the transmitting side receives an acknowledgement, a new data packet is sent. This is important when you must receive every piece of information from the base or transmitting site. If the transmitting side does not receive an acknowledgement back from the receiving side in the specified time (e.g. .5 sec), it retransmits the data again. The receiving side can also send back a message saying it received a bad data set and request a re-transmission of the data. This can be very time consuming if there is any noise in the system requiring re-transmissions. In the case of RTCM-104, each data set stands on it's own so that if you miss a data packet, the next one you receive will take care of the problem (as long as the next data packet is not too far in the future). One option may be the no-acknowledgement mode (if available). In this configuration the data is shipped as received with no-acknowledgement shipped from the receive side or expected on the transmit side. The receiving side uses every packet it can understand or that it receives. Whether or not you can use this option depends on your requirements and equipment.

Example 2:
Packetization or no packetization can help or hinder the AOC value. Packetization refers to the way the data is handled or processed before transmission. A system that packetizes the data will normally wait for some signal or event before transmitting its data. It may only transmit after

receiving a set amount of data or when it sees a gap in the data. Error correction and detection information may be added to the data so that the receiving equipment can tell if it has a bad data set and can it correct (or re-create) the original data without requesting a re-transmission of the original data. Some systems do no packetization but start transmitting after any "set up" delay and stop transmitting when they have no more data to send. Most satellite systems use some form of packetization and error correction or determination. Sometimes it is a configuration option on radio systems.

Packetization can hurt you in ways you would not expect. If you are shipping correction data from your GPS base station to your radio or transmitting system at 300 baud, that requires a full packet (however defined) before it sends the data, you are penalizing yourself with an unnecessary additional delay of 2.5 seconds (using 8 satellite type 1 RTCM-104 correction) before adding any other system delay. If you ship your data to your radio equipment at 1200 baud, the additional latency is only .7 seconds. In systems where no packetization is performed you should send your data to the transmitting equipment at least as fast as the rate at which it transmits the data for minimal additional latency; the faster the better.

V) RTCM 104 - STANDARD

The RTCM 104 standard was developed to address meter positioning requirements for stations separated up to 100 km using slow 50 baud rate data link. The RTCM-104 standard defines the generating and formatting method of the DGPS corrections. The standard enables using equipment from different manufactures at monitor and remote stations. The common differential method applied in RTCM-104 is mathematically described by equations (1) to (4). Although RTCM 104 is a well accepted standard in the industry, some improvements are still possible. There exists extensive literature on RTCM 104 (Kalafus et al, 1985). The following points can be made about RTCM 104 based DGPS:

- The RTCM-104 format is not the most efficient method for transmitting data. First, as implemented by the GPS equipment manufacturers, it is a "6 of 8" system; six (6) bits of binary data are mapped into a eight (8) bit data byte. This produces an ASCII printable data string that most satellite and terrestrial equipment can transmit without problem. Some satellite systems cannot transmit true binary data because they use the upper two bits for system signaling, which causes a 25% throughput penalty. Second, the RTCM SC-104 data format is the same as that used for downlinking data from the NAVSTAR satellites and was chosen so as to allow the same decoding schemes to be used. Each "word" is made up of 30 bits of data the last six of which are parity bits, which is 20% of the data transmitted. The first two words of every RTCM-104 message are identity and status information, 60 bits total, 10 bytes on the "6 of 8" format. Going to a raw data format or even a modified RTCM format can provide better throughput on any data link.

- The RTCM 104 source does not address differential tropospheric and ionospheric corrections. It is assumed that atmospheric effects are eliminated through differencing. It is not a valid assumption for meter level DGPS accuracy for distances longer than 100 km. The atmospheric effects are not taken into account to avoid using incompatible models at monitor and remote ends. However, one should notice that the problem of incompatible models can be circumvented

if differential atmospheric effects are computed at the user end. The user will use the same model to compute atmospheric corrections for monitor and user ends. One only needs to know the approximate coordinates of both stations. Although computing the differential atmospheric corrections is easy to implement, it is not employed in the commonly used GPS receivers.

- RTCM 104 based DGPS requires an expensive base station that generates pseudorange corrections. The base station hardware is comprised of a GPS receiver that tracks pseudorange and carrier phase. There are now low-cost but high quality GPS receivers (Magnavox MX4200, NovAtel) that do not output RTCM 104 corrections but can be used in principle for cost-effective DGPS positioning.

- RTCM 104 does not address a case of multi-site DGPS when corrections are available from several reference stations.

VI) DGPS SYSTEMS USED IN THE STUDY

Several real time differential systems, either RTCM-104 based or those developed in house, were used in this study. RTCM-104 based DGPS systems are well known and therefore are not described in detail here. They consist of a base station generating pseudo-range corrections in RTCM-104 format and at least one user receiver applying corrections to its solution. Typically, the base station is more complex than the user receiver, has more than 6 tracking channels and therefore is more expensive than the user receiver.

Alternate application-range oriented DGPS systems, described below were developed by JECA and were also used in this study. These systems are either more cost-effective or more accurate in certain applications than basic RTCM-104 based systems. Their common feature is modelling the differential tropospheric and ionospheric effects. They are built around low-cost MX4200 GPS receivers and are briefly described below. The intention is to introduce them for easy reference in an analysis rather than to describe algorithmic and operational details. The systems used are summarized in Table 2.

- Local DGPS (LDGPS)

The Local DGPS system consists of an MX4200 receiver at the base station, another MX4200 and a computer at the remote station, and UHF data link between them. The MX4200 GPS receiver does not output pseudorange corrections, but raw GPS observations. In order not to have an additional computer at the reference station, GPS pseudoranges are transmitted directly to the user. The pseudorange corrections and their rates are generated and applied to the DGPS solution at the remote station. The computational method used is equivalent to the method recommended by RTCM 104, and described by equations (1) to (4). The difference is that pseudorange corrections are not computed at the monitor end but at the user end. The main advantage of the system is high quality DGPS positioning comparable to other systems, but at lower hardware cost. The system uses UHF link for close range (20km) operations and HF link for longer range operations.

SYSTEMS USED	MONITOR	REMOTE	DATA LINK	TELEMETRY DATA	ATMOS-PHERIC MODEL	POST PRO-CESSING	REMARKS
RTCM SC-104 based	base station	MX4200D, Trimble 4000SX	satellite 600 baud	RTCM 104	No	No	
WADGPS	multiple base stations	MX4200, computer, JECA software	satellite 600 baud	RTCM 104	Yes	Yes	weighing individual solutions
LDGPS	MX4200	MX4200, computer, JECA software	UHF/HF	raw pseudoranges	Yes	Yes	PRC computed at remote end. No computations at monitor.
delta pseudo-range	MX4200, computer, JECA software	MX4200	UHF	raw pseudoranges	N/A	Yes	* Monitor station is moving. Time matching of monitor and remote GPS ranges.

Table 2
DGPS systems used in the study

- Multi-Site Wide Area DGPS (WADGPS)

The Multi-Site Wide Area DGPS system combines differential corrections from seven JECA DGPS stations covering the United States (Fig. 1) to get the optimal estimate of user position. The weighted averaging of the single baseline DGPS solutions is used. The use of several DGPS stations enables reduction of systematic effects and thus extends the operation range of typical stand-alone DGPS systems from 100 km to at least 1000 km without accuracy degradation. The differential corrections are transmitted via STARFIX, a geostationary satellites based system. The system used in this study, although specifically designed for long-range operations in the Gulf of Mexico, can be used anywhere in the United States.

John E Chance Differential GPS Continental Network

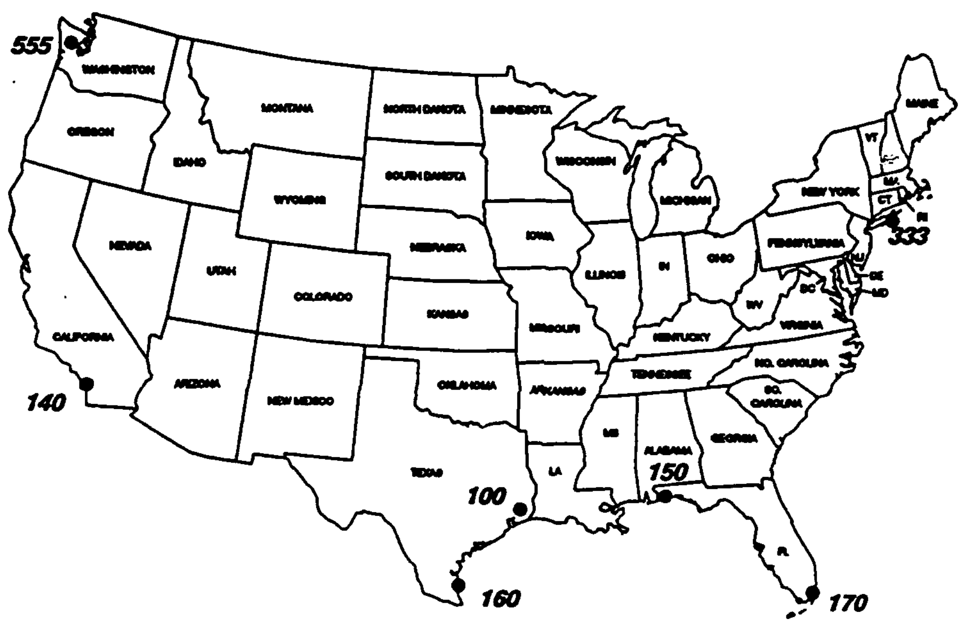

Fig 1 John E. Chance DGPS Network

- Delta pseudorange DGPS

The system uses the difference of time-matched pseudoranges from equation (5) to determine the relative position of remote objects with respect to the moving master-platform. The employed method "delta pseudorange" implies that only common satellites are used in a solution. The system has a high-speed data link. Since only time-matched observations are used and distances involved are small (typically less than 15 km) , the determined relative positions are not affected by Selective Availability. The system has been used to track Tailbuoys towed by seismic ships for Cable Positioning.

Two real-time simulators were also used in the investigation. The multi-site WADGPS simulator processes the recorded MX4200 and RTCM 104 corrections in the same sequence as they were recorded in real-time. The simulator for the real time LDGPS system is more general. It processes raw range data from reference and user ends. It generates pseudorange

corrections and their rates using reference station data and applies to user data with user-defined data rate and options (2D or 3D, elevation and DOP masks etc.) to simulate a variety of real-time conditions.

MX4200 receiver data is used mainly in the investigation. MX4200 is one of the best receivers on the market in terms of raw GPS data noise. See (Kielland and Neufeldt, 1991) for a performance comparison of different GPS receivers. Analyzing a MX4200 data provides a good assessment of DGPS accuracy that can be achieved with other receivers as well.

VII) DATA COLLECTION, ANALYSIS AND RESULTS

A. METHOD OF ANALYSIS

The results of both real-time and simulated real-time DGPS are presented below. Each real-time experiment is unique by its nature and cannot be repeated with the same conditions. Therefore, the raw GPS data was collected and post-processed to study the influence of different factors on DGPS accuracy using the same data set.

In the following, the multisite and single site DGPS solutions are given. The non-differential position errors are also presented to show the level of SA activity. Four Gulf of Mexico DGPS stations are used in multi-site solution namely: Houston (330 km), Mercedes TX (730 km), Pensacola FL (460 km) and Miami FL (1300 km), where the number in parentheses gives the station separation from Lafayette. These stations are numbered 100, 150, 160, and 170 on Figure 1. Throughout the analysis, all differential results are referenced to the known coordinates of the control point at Lafayette.

24 hour DGPS results from different days were used in the analysis. We believe that daily data sets provide a realistic assessment of day-to-day DGPS accuracy.

The DGPS accuracy is given in terms of mean error and root mean square error of position components. The first one represents bias, while the second one the noise level of the solution. Most presented results are height constrained 2D solutions. However, the comparison of 2D and 3D results is also given as part of the analysis.

B. IMPACT OF SELECTIVE AVAILABILITY

Selective Availability (SA) has been on from November, 1991. Since that time different levels of SA activity have been exercised. SA degrades the accuracy of the stand-alone position obtained using the C/A code. The Federal Radio Navigation Plan, 1991 states that this degradation will be not worse than 100 m 2dRMS. The effects of typical SA are almost completely removed using the differential method. The degree of error cancellation depends on the size of SA error itself, the distance from monitor station and update rate of pseudo-range corrections at the remote sites.

1) Typical Selective Availability

The GPS user can access the level of Selective Availability by monitoring the GPS stand-alone point position error. This error is typically at a few tens of meters level. In addition, the DGPS user can monitor the pseudo-range corrections and their rates. Typically, the pseudo-range corrections are below 100 meters while pseudo-range correction rates are under 0.5 meter/seconds.

The pseudo-range corrections are blended satellite orbit and clock, tropospheric and ionospheric errors expressed by equation (6). The correction rates express the changes in time of the determined pseudo-range corrections mainly due to SA satellite clock dithering. If SA were off, the correction rates would be close to zero due to slow change of orbit, tropospheric and ionospheric errors. Therefore, monitoring the correction rates provides quick check for SA presence.

Data from day 57, 1992 (February 26) was chosen as representative sample of a typical SA activity. The results presented below have been repeatable for most of time from November 1991.

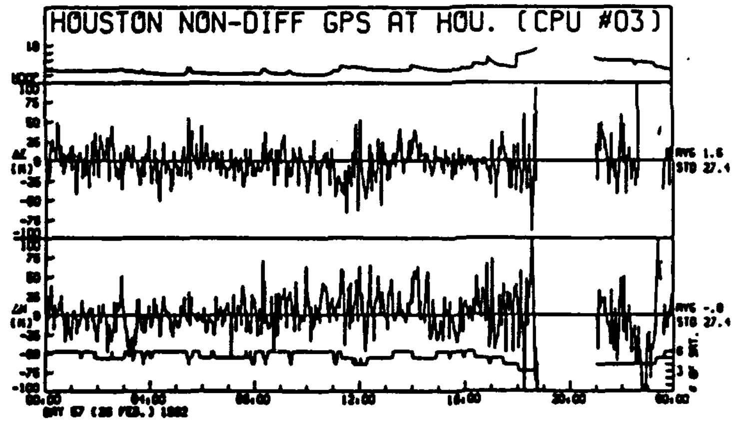

Fig 2 Non-differential GPS Results (Meters),
Typical SA, Day 57

The non-differential, single site 330 km and multi-site solutions for day 57 are given in Figures 2 to 4. The single site results are obtained with application of RTCM 104 corrections which were then corrected for effects of troposphere and ionosphere. The section D, that follows, has a comparison of the DGPS results obtained with using and without using differential atmospheric corrections. The multi-site results were obtained using pseudo-range corrections from the four Gulf of Mexico monitor stations shown in Figure 1. Note, that multi-site solution includes a 330 km baseline.

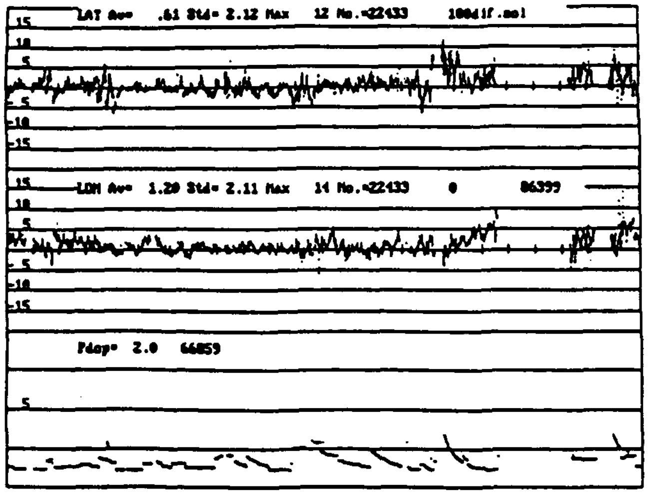

Fig 3 Single-site 330 km DGPS Results (Meters), Typical SA, Day 57

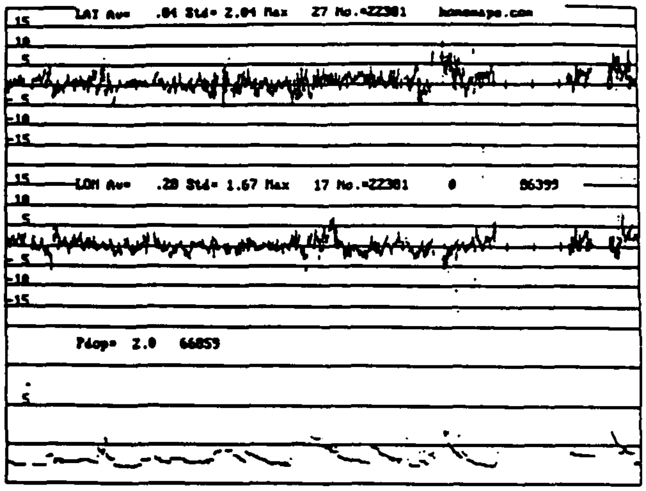

Fig 4 Multi-site DGPS Results (Meters), Typical SA, Day 57

Figure 3 represents the positioning results that can be achieved today with typical DGPS systems. After analyzing Figure 3, several general comments can be made. First, it is important to note that, unlike radio or laser systems, GPS position errors are not homogeneous. The errors are not constant or uniform, but they change as the satellite geometry changes. As error sources such as ionosphere, troposphere, multipath change, the system response to the changes takes effect.

Second, the effect of PDOP (Position Dilution of Precision) on the position accuracy cannot be understated. Any error in the pseudorange will be multiplied by the PDOP factor and reflected in the final position. A 3 meter error in the pseudoranges will translate to a 6 meter position error when the PDOP is 2. The PDOP plot for the analyzed day is shown at the bottom of Figure 3.

Third, most of the excursions are directly related to constellation changes (noted as a discontinuity in the PDOP value). Other excursions can be caused by multipath.

Finally a redundancy of solution is an important factor affecting DGPS accuracy. Five or six satellite solution is usually stronger than three or four satellite solution. Redundant satellite ranges can provide improved geometry and better quality control of the solution.

In summary, while there are times when position error exceeds the target of 3 meters, overall the horizontal position accuracy is better than 3 meters.

Figure 4 presents comparable multi-site results. Multi-site means that DGPS position is obtained using pseudo-range corrections from three longer baselines in addition to 330 km baseline. Comparison of results from Figures 3 and 4 reveals accuracy improvement of multi-site solution (latitude rms 2.0 meter, longitude 1.7 meter) over single site solution (latitude rms 2.1 meter, longitude rms 2.1 meter). Adding more reference stations helps to eliminate errors in the monitor part of the DGPS system. Obviously the errors in the remote user receiver are still present, which is why both plots are correlated.

2) Extreme Selective Availability

Extreme Selective Availability was encountered on November 23, 24 and 30 (days 327,328 and 334) of 1991, respectively. The non-differential, single site and multi-site solutions for these days are given in Figures 5 to 13.

The clock dithering was approximately of the same order on these two days. The range rates were, on average, at the level of 1 to 1.5 meter/second. However, on day 327 the pseudo-range corrections were reaching several thousand meters and on days 328, 335 several hundred meters. Note that on these days most of the non-differential errors are outside the 100 meter scale on Figures 5, 8 and 11. Moreover the pseudorange-corrections were varying spatially - their size was different at different points on the JECA DGPS network. It implied that orbit errors were significantly bigger than during normal SA activity. It deteriorated the DGPS results beyond acceptable limits on long baselines on the days 327 and 328. Note, however, that multi-site DGPS has again reduced error compared with single site DGPS.

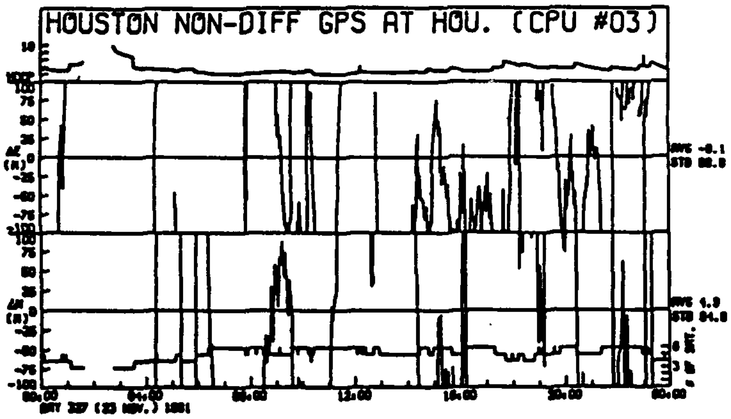

Fig 5 Non-differential GPS Results (Meters), Extreme SA, Day 327

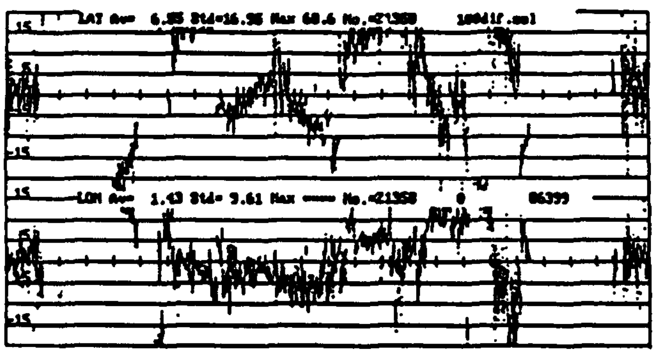

Fig 6 Single-site 330 km DGPS Results (Meters), Extreme SA, Day 327

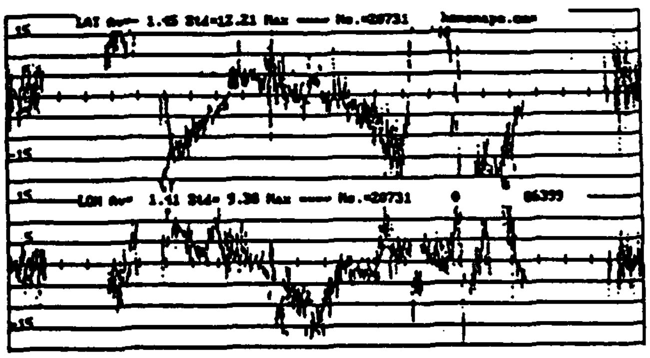

Fig 7 Multi-site DGPS Results (Meters), Extreme SA, Day 327

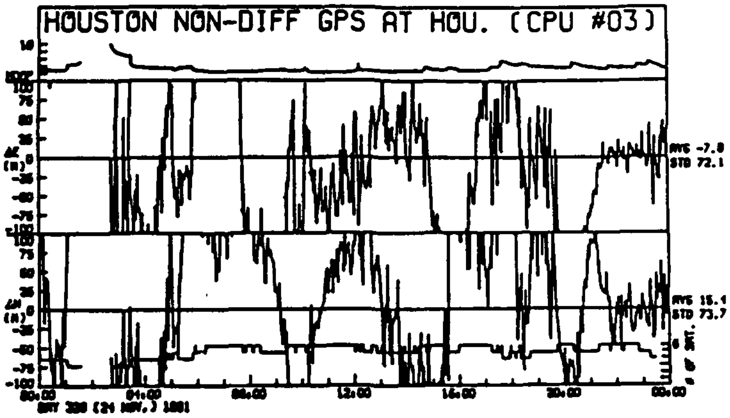

Fig 8 Non-differential GPS Results
(Meters), Extreme SA, Day 328

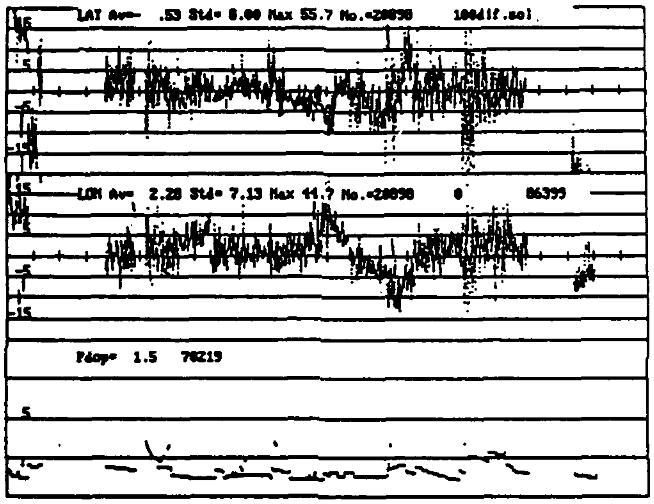

Fig 9 Single-site 330 km DGPS
Results (Meters), Extreme SA, Day 328

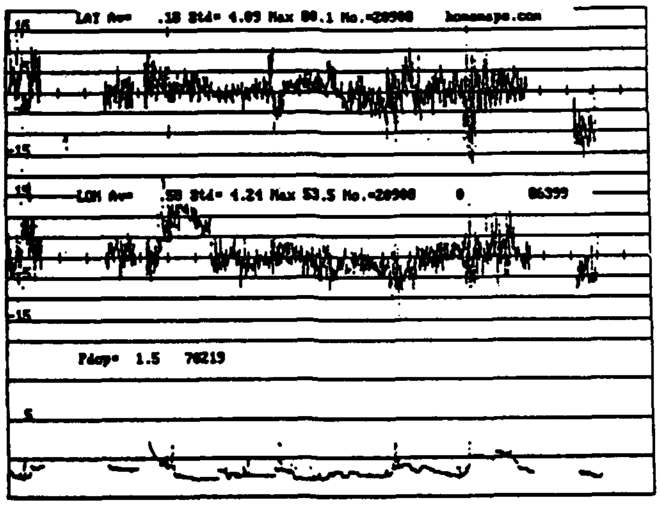

Fig 10 Multi-site DGPS
Results (Meters), Extreme SA,Day 328

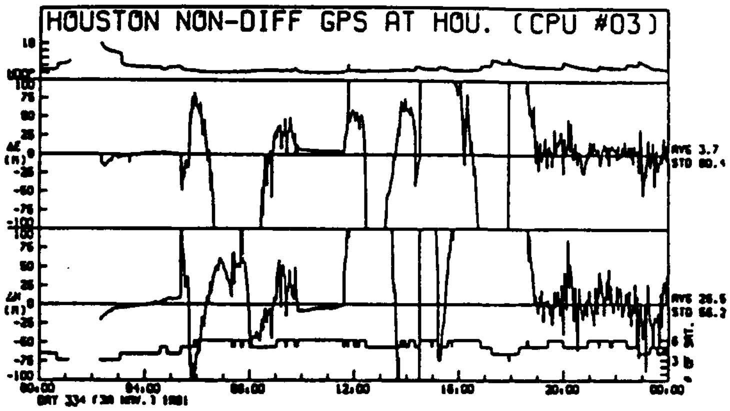

Fig 11 Non-differential GPS Results (Meters), Extreme SA, Day 334

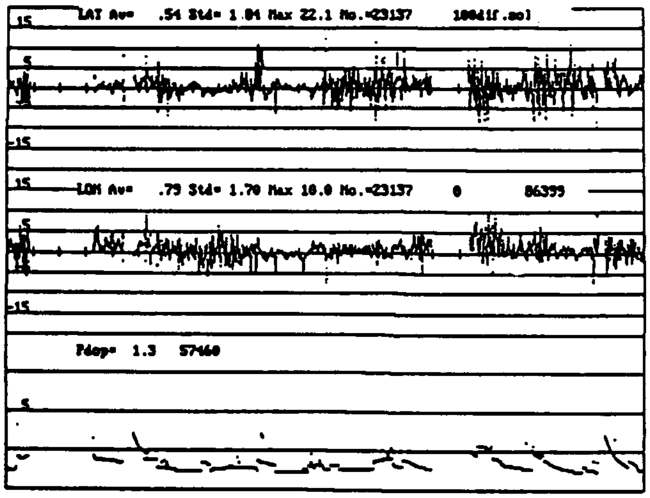

Fig12 Single-site 330 km DGPS Results (Meters), Extreme SA, Day 334

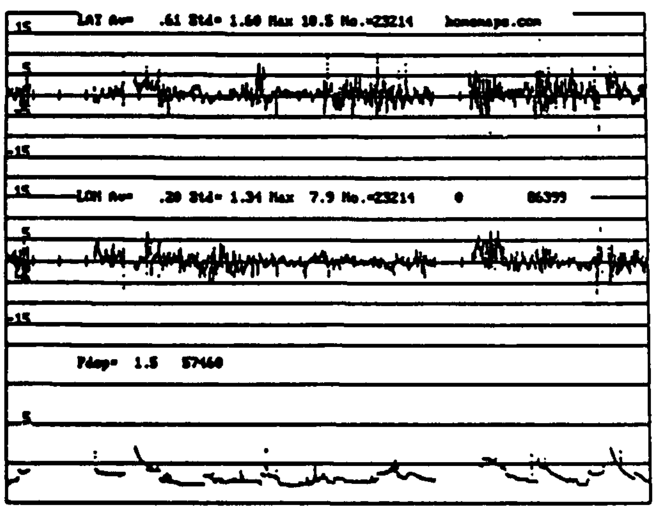

Fig 13 Multi-site DGPS Results (Meters), Extreme SA,Day 334

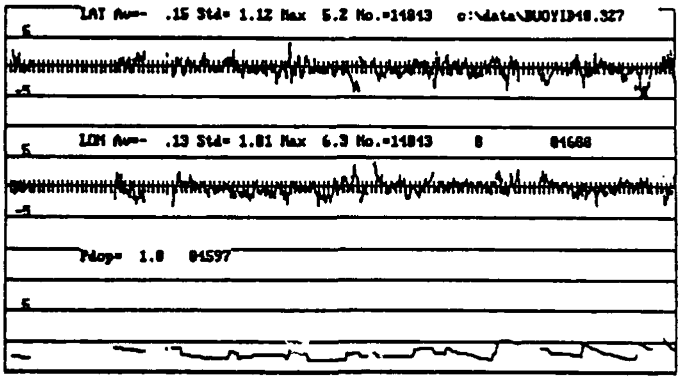

Fig 14 Time-matched 0.3 km DGPS
Results (Meters), Extreme SA, Day 327

Figure 14 shows the results from time-matched delta pseudorange DGPS on short baseline (300 meters) from the most severe SA, day 327. Even though SA was the most severe on this day, all SA effects were effectively removed by differencing. The satellite clock errors were completely removed with time-matched observations from two GPS receivers. On the other hand the huge orbit error had no effect with such a short distance.

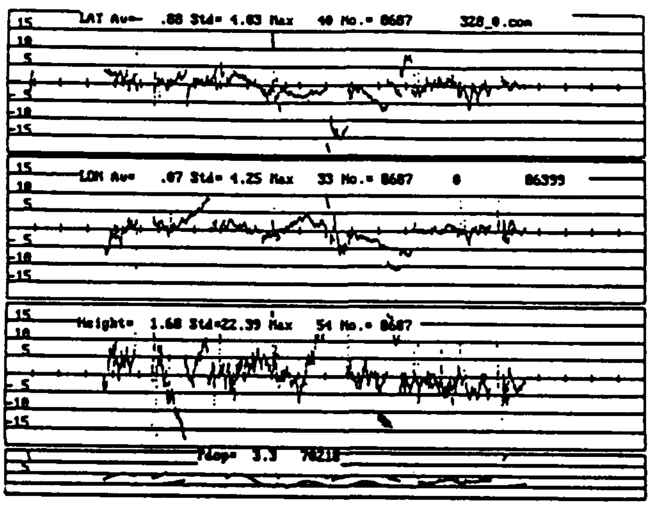

Fig 15 Time-matched 330 km DGPS
(Meters), Extreme SA, Day 328

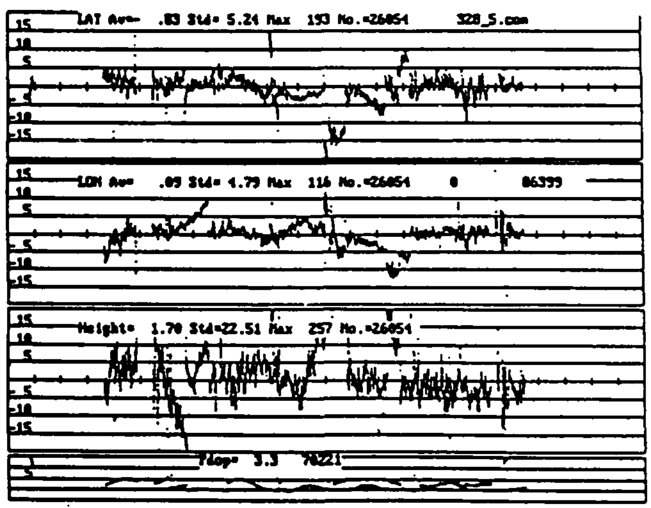

Fig 16 330 km DGPS Results with 5 seconds
Update Rate (Meters), Extreme SA, Day 328

Figure 15 shows the influence of station separation on DGPS accuracy also during a period of heavy SA, on day 328. This figure presents postprocessed differential results of MX4200 data collected on 330 km Houston - Lafayette baseline. Note, that the results on Figure 15 were obtained using time-matching of GPS observations as in the case of Figure 14. However, the results from Figure 15 are significantly worse than these from Figure 14. It implied that orbit error was the main factor contributing to DGPS accuracy on these days. This statement is further proved with results from Figure 16.

Figure 16 presents the postprocessed DGPS results using the same data as in the case of Figure 15, but with 5 seconds update rate of differential corrections to simulate real time. Although an overall error was increased due to the non-linear effects of clock dithering, the increase of the error was not as visible as in the case of transition from Figure 14 to Figure 15, which is from a short to a long distance.

C. EFFECT OF UPDATE RATES

Special numerical tests were performed to determine the position errors due to residual non-linear SA satellite clock errors at different update intervals. In order to separate the influence of these errors from other DGPS errors, the collected raw MX4200 data set from one GPS receiver was processed differentially against itself with specific update intervals.

The method used simulates an experiment when two receivers, monitor and remote, have exactly the same noise and run from the same antenna. In this way, spatially correlated errors (orbit, tropospheric and ionospheric) and multipath errors are canceled. Therefore, the obtained position errors can be directly attributed to the influence of residual non-linear SA clock dithering effects.

Although raw pseudorange data is used for analysis, the obtained results are representative for RTCM-104 based systems because the same pseudorange correction generation and application algorithms, as in RTCM-104, are used. In other words, the method exploits the fact that a contribution of SA clock dithering to the DGPS error is a function of an update rate, but not the type of receiver, provided the computations are done correctly.

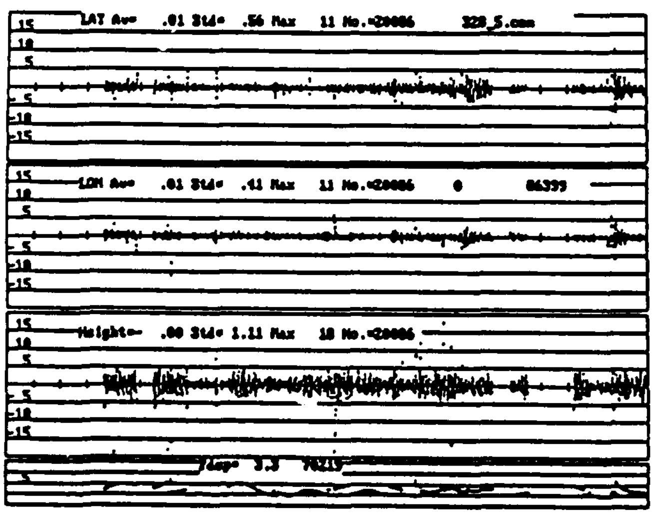

Fig 17 Residual SA Effects at 5 seconds Update Rate (Meters), Extreme SA, Day 328

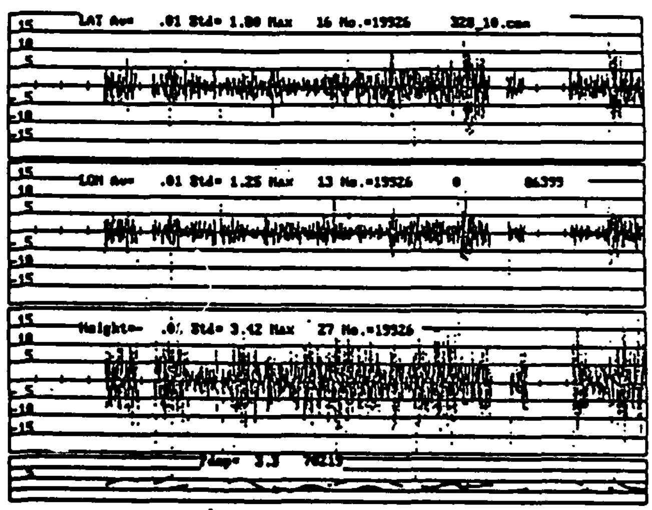

Fig 18 Residual SA Effects at 10 seconds Update Rate (Meters), Extreme SA, Day 328

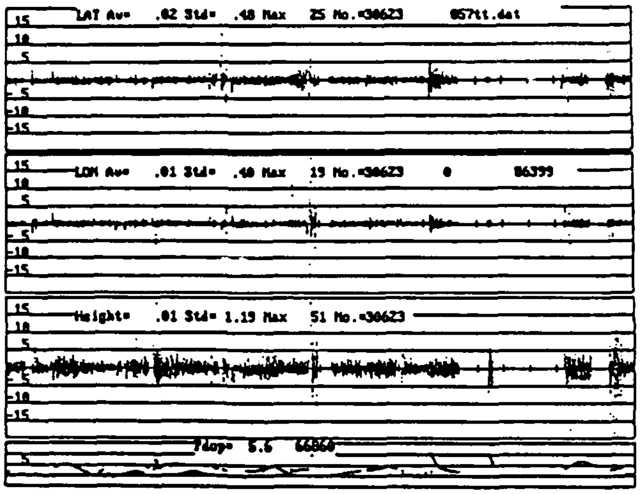

Fig 19 Residual SA Effects at 5 seconds Update Rate (Meters), Typical SA, Day 57

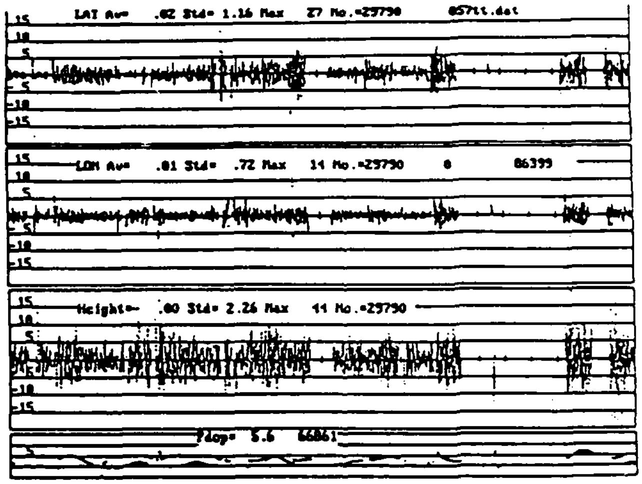

Fig 20 Residual SA Effects at 10 seconds Update Rate (Meters), Typical SA, Day 57

Figures 17 to 20 show the computed DGPS position errors due to residual non-linear SA clock errors using 5 and 10 sec update intervals for day 328, 1991 and day 57, 1992 respectively. Recall that day 328 represents a heavy SA while the day 57 a typical SA. The comparison of results from both days is surprising. The respective plots show approximately the same bandwidth of residual errors. Having in mind earlier observations of different sizes of pseudo-range correction rates at these days, the obtained similar residual errors suggest that only the amplitude of clock dithering is changed during different SA days, but the frequency remained the same.

However, the major conclusion is that a five second update rate enables one to keep the contribution of SA clock errors less than one meter. On the other hand this update rate is easily obtained with the modern data links analyzed in section IV.

The results suggest a rule of thumb that unaccounted satellite clock errors contribute to final position error, on average 0.1 meter in latitude and longitude and 0.2 in height per every second of update rate. This is true for update rates up to 10 seconds. In general, position error due to residual SA is non-linear and grows asymptotically.

D. COMMON DGPS TEST

The study performed so far was focused on the influence of Selective Availability on DGPS accuracy and was carried out using the systems and methods developed in house. This has been a valid approach because SA influence on a determined position should not be dependent on the type of the system used. However, to validate the results, a performance comparison of different systems is necessary.

A special test was carried out on February 23, 1992 (day 53) in order to compare the performance of different real-time DGPS systems under the same operational conditions. In

addition, the systems of the same type were used simultaneously, at different baselines to study the influence of the DGPS station separation.

The non-differential solution on this day is shown in Fig. 21. The small horizontal position error indicated that Selective Availability was off during this day. That event, although not anticipated, enabled direct comparison of the DGPS results when SA was off and on.

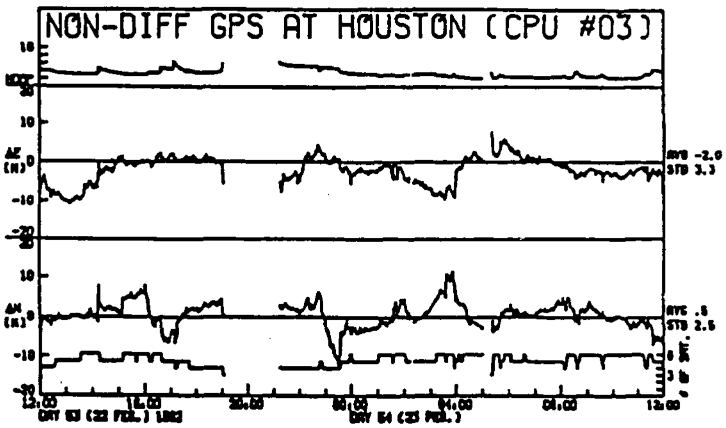

Fig 21 Non-differential GPS Results
(Meters), No SA, Day 53

Trimble 4000 SX, Magnavox MX4200D and WADGPS differential systems were placed at known points close to the JECA Lafayette office. All three systems were using RTCM-104 corrections received at 600 baud rate via STARFIX satellite link. The first two systems were using the pseudorange corrections from a base station in Houston separated by 330 km, while the WADGPS system used four Gulf of Mexico stations. All systems were positioning in height constrained 2D mode, using 10 degrees elevation mask and PDOP mask of 4.

The position output of these three systems was recorded. The WADGPS system was also logging raw MX4200 data and RTCM-104 corrections for post-processing purposes. In addition, on the same day, raw MX4200 data was collected at known points in New Orleans, LA. and New Roads, LA., 190 and 80 km north-east from Lafayette respectively, to investigate the station separation influence on accuracy. The results from the 190 km and 80 km baselines are denoted as LDGPS 1 and LDGPS 2, respectively. The data from these stations were combined with MX4200 data collected at the Lafayette office using LDGPS real time simulator.

First, consider the results of the three systems; Trimble 4000 SX Magnavox MX4200D and the system denoted as Single Site (WADGPS also uses one site). Recall that they all used the differential corrections from the same monitor station. In addition, single site system used GPS observations from the same MX4200D receiver at the remote end. The real-time horizontal position results from the three systems are shown in Figures 22 to 24. The test statistics are summarized in first three rows of Table 3.

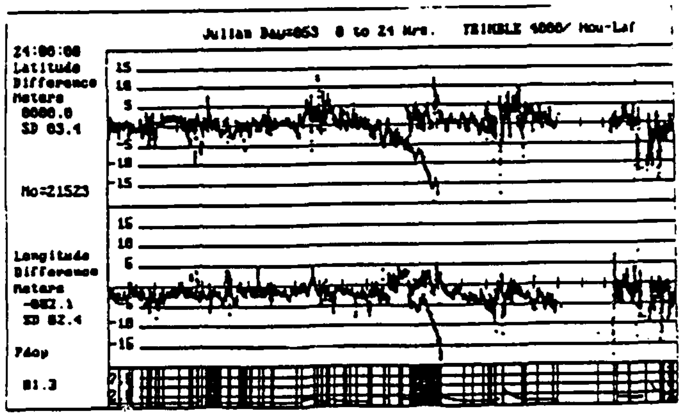

Fig 22 Trimble 4000SX, 330 km DGPS Results (Meters), Day 53

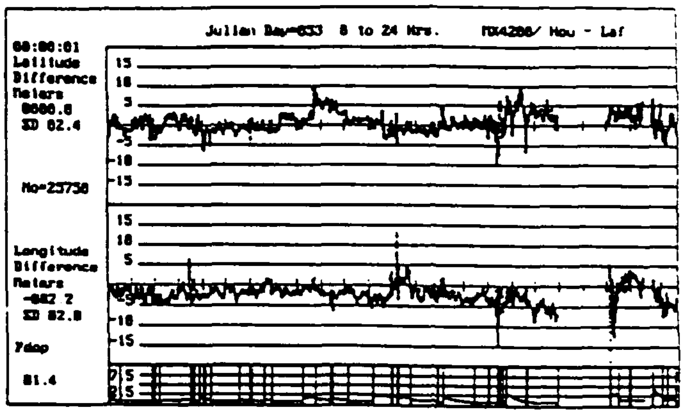

Fig 23 MX4200D, 330 km DGPS Results (Meters), Day 53

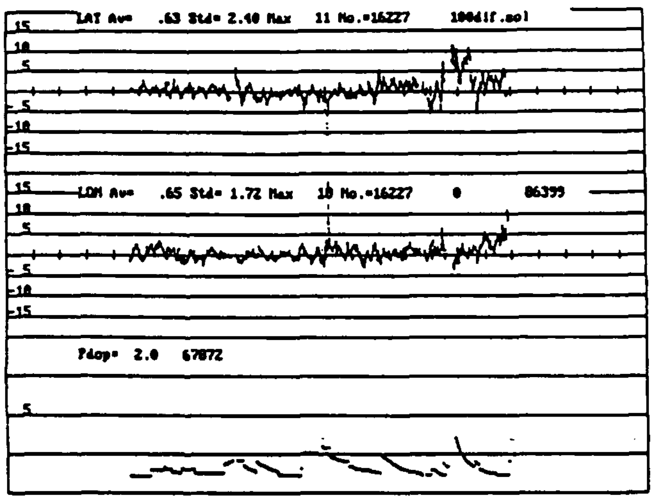

Fig 24 Single-site 330 km DGPS Results (Meters), Day 53

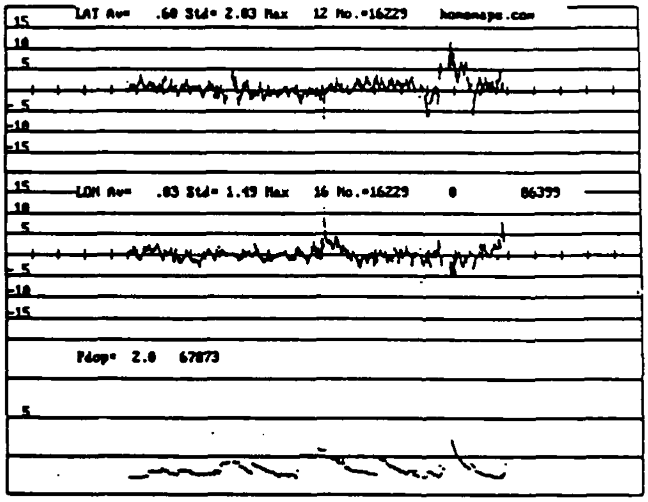

Fig 25 Multi-site DGPS Results (Meters), Day 53

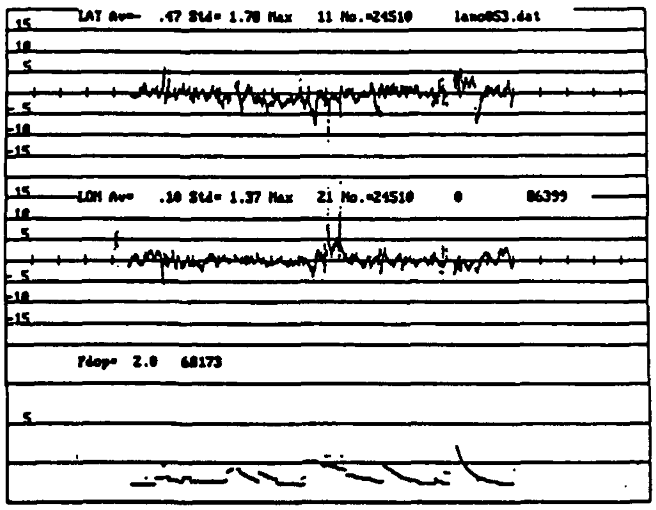

Fig 26 Single-site 190 km DGPS Results (Meters), Day 53

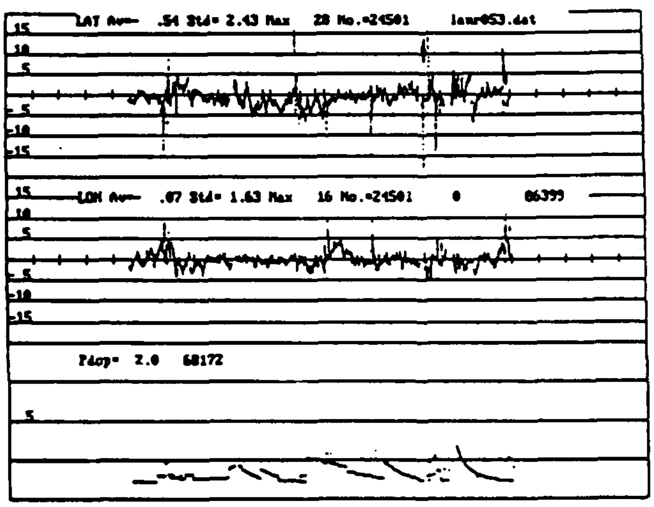

Fig 27 Single-site 80 km DGPS Results (Meters), Day 53

	LAT		LON		
SYSTEM	MEAN	RMS	MEAN	RMS	FIGURE
4000SX	0.0	3.4	-2.1	2.4	22
MX4200D	0.8	2.4	-2.2	2.0	23
SINGLE SITE	0.6	2.4	0.6	1.7	24
WADGPS	0.6	2.0	0.0	1.5	25
LDGPS 1	-0.5	1.8	0.1	1.4	26
LDGPS 2	-0.5	2.4	-0.1	1.6	27

Table 3
2D Results (Meters) - Day 53

Both the Trimble 4000 SX and the MX4200D results show an approximate 2 meter bias in longitude. Single site results are correlated with MX4200D results because they share the same GPS receiver at the remote end. However, the single site solution does not show a bias in longitude and has a slightly reduced noise level as well. These better results are achieved due to applying the tropospheric and ionospheric differential corrections.

Compare now, the results of these three systems to multi-site DGPS, given in Figure 25 and summarized in fourth row of Table 3. The multi-site results are superior both in terms of average error and rms. It confirms, what was already argued, that using multiple reference stations improves DGPS accuracy.

Second, compare the results from Figures 24 and 25 (SA off) to the respective results from Figures 3 and 4 when SA was on. This comparison reveals that there is no accuracy degradation when SA was turned back on for distances under 300 km. Under 300 km the present SA orbit error did not affect the results. The main part of SA error is attributed to clock dithering. This error, on the other hand, is effectively removed with fast pseudo-range correction update rates of five seconds or less.

Third, the last two rows of Table 3 show the statistics of differentially processed MX4200 data from 190 km and 80 km baselines using LDGPS real-time simulator with 5 sec update rate and applying the differential tropospheric and ionospheric corrections. Distance is not a factor in these two cases because the systematic effects have been removed. The final error is only due to receiver noise and multipath.

E. 2D MODE VERSUS 3D MODE

It is well known that height is the weakest component of the position determined by the GPS. It is due to higher correlation of height with GPS range errors than respective correlation of horizontal position. In many DGPS applications i.e. ship positioning, only horizontal position is of interest. In this case, height constrained 2D mode is usually employed. It is based on the

assumption of known user WGS 84 ellipsoidal height and hence one unknown is reduced. This enables using a minimum three satellites for the GPS fix and overdetermination in a case of four or more. Overdetermination is very desirable for quality control of the solution.

However, the user ellipsoidal height used in a solution may be different from true height. This may be due to uncounted vertical motion of the ship with respect to the ellipsoid due to earth tides or waves. The error can be also caused by an inaccurate value of the geoid separation used for computing of the ellipsoidal height.

The following questions can be asked:

- what is the accuracy of horizontal position determined by DGPS in a 2D and 3D mode
- what is the accuracy of height determined using DGPS in a 3D mode
- how well should the user ellipsoidal height be known to be used in constrained 2D mode without horizontal position accuracy degradation.

In order to answer the first two questions the collected data from Day 53 was reprocessed in a 3D mode. The latitude, longitude and height results from the respective systems are shown in Figures 28 to 31. Compare these results with respective 2D results in Figures 24 to 27. The 3D test statistics are summarized in Table 4. Compare these statistics to last four rows of Table 3.

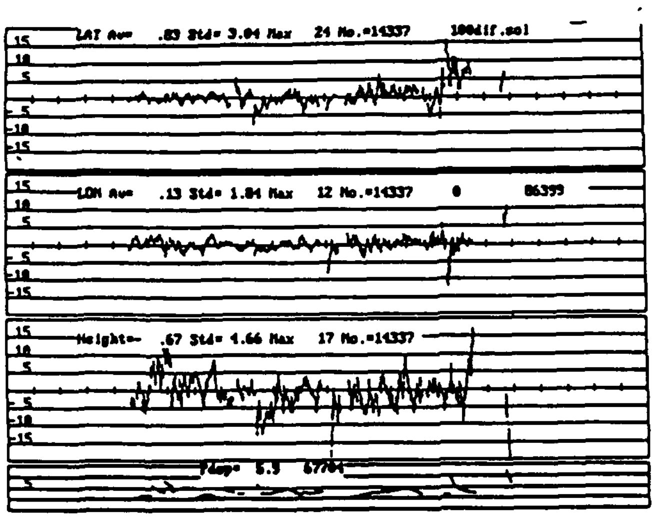

Fig 28 Single-site 330 km DGPS
3D Results (Meters), Day 53

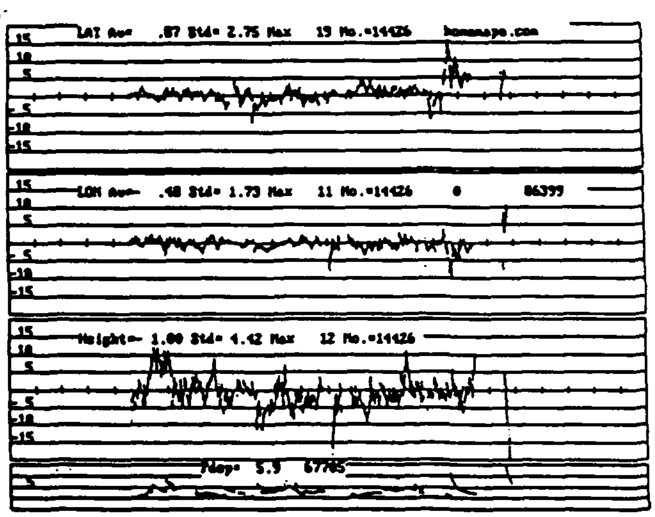

Fig 29 Multi-site DGPS
3D Results (Meters),Day 53

The results show a similar pattern of horizontal position error in comparison with the 2D results but with a slightly larger noise level. A degradation of accuracy might be attributed to worsening geometry of the solution in certain cases of 3D mode. Overall, they are at 2.5 and 2 meters level for latitude and longitude respectively. The height error is at 4-5 meters level and on average is twice as large as latitude and longitude errors.

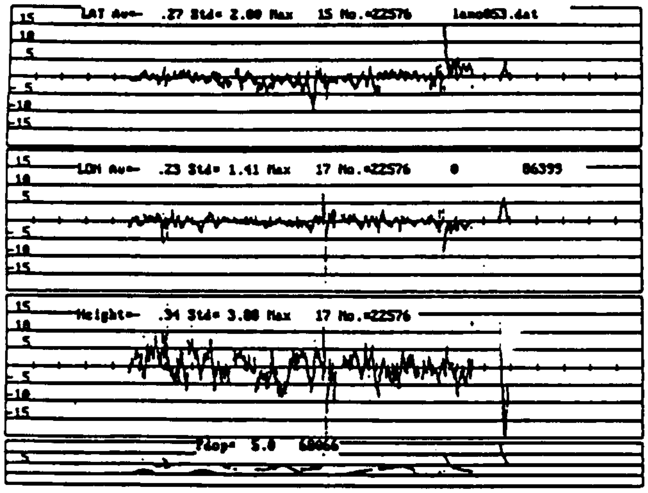

Fig 30 Single-site 190 km DGPS
3D Results (Meters) - Day 53

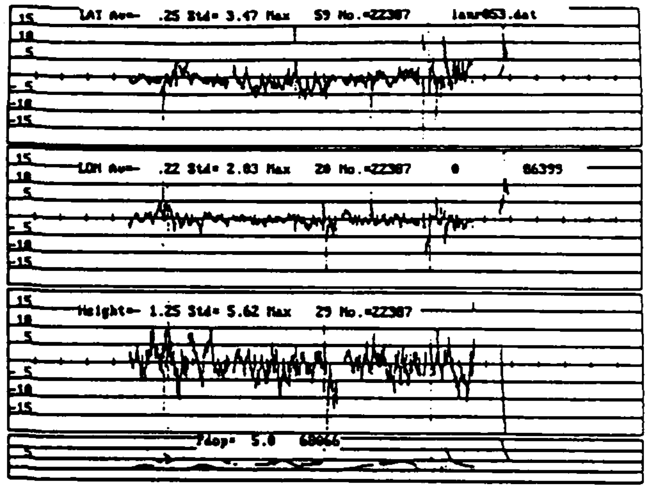

Fig 31 Single-site 80 km DGPS
3D Results (Meters) - Day 53

	LAT		LON		HEIGHT		
SYSTEM	MEAN	RMS	MEAN	RMS	MEAN	RMS	FIGURE
SINGLE SITE	0.8	3.0	0.1	1.8	-0.7	4.7	28
WADGPS	0.9	2.7	0.5	1.7	-1.0	4.4	29
LDGPS 1	0.3	2.0	0.2	1.4	-0.3	3.9	30
LDGPS 2	-1.2	3.5	0.2	2.0	-1.2	5.6	31

Table 4
3D Results (Meters), Day 53

The third problem of inaccurate remote station ellipsoid height was investigated by introducing a 3 meter error bias in the user ellipsoidal height. This is typical height error that might be expected in production environment, based on our experience. The data was reprocessed again in a 2D mode. The latitude and longitude errors are shown in Figures 32 to 35. The test statistics are summarized in Table 5.

The conclusion drawn from comparing Table 5 with Table 3 is that error in height produces a much smaller error in horizontal position. The height bias is mapped mostly into clock error due to their high correlation and has only a reduced effect on horizontal position. Therefore use of height-constrained 2D mode is justified under normal conditions.
The term normal condition in this case means, that user does not experience any unaccounted vertical motions bigger than five meters.

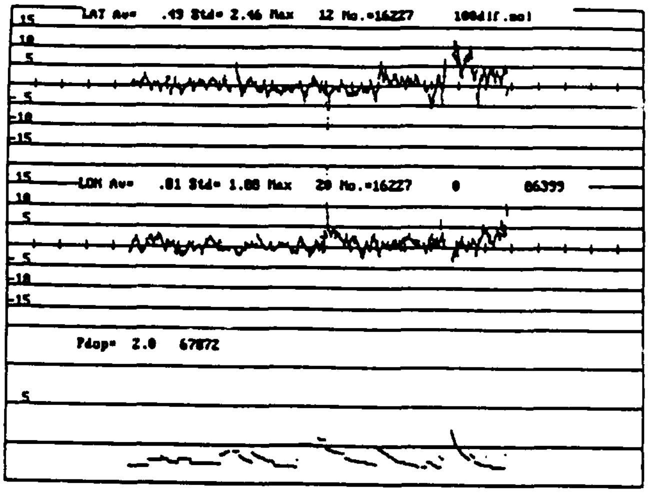

Fig 32 Single-site DGPS 2D Results with 3 meter Height Bias (Meters) - Day 53

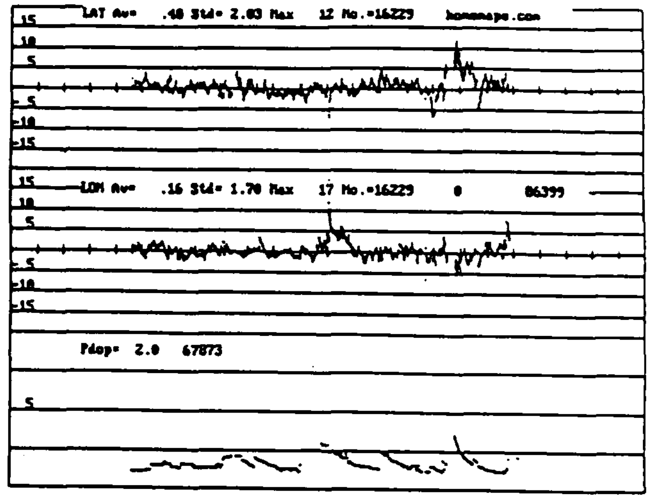

Fig 33 Multi-site DGPS 2D Results with 3 meter Height Bias (Meters) - Day 53

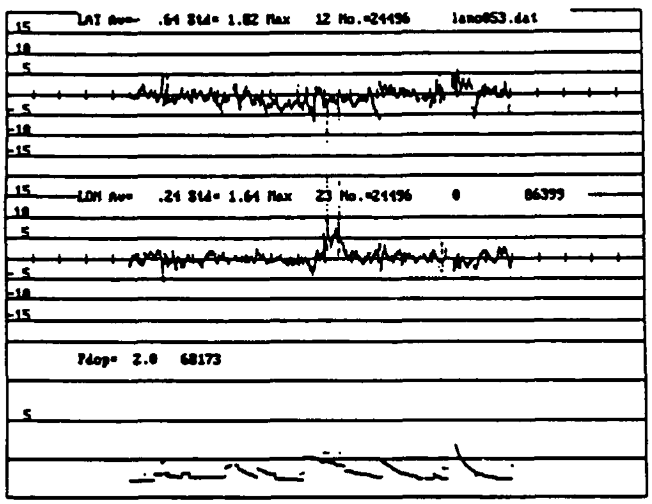

Fig 34 190 km DGPS 2D Results with 3 meter Height Bias (Meters) - Day 53

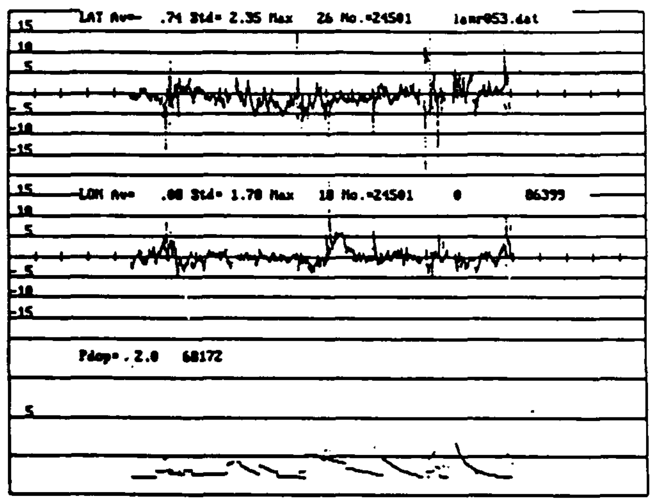

Fig 35 80 km DGPS 2D Results with 3 meter Height Bias (Meters) - Day 53

	LAT		LON		
SYSTEM	MEAN	RMS	MEAN	RMS	FIGURE
SINGLE SITE	0.5	2.0	0.2	1.7	31
WADGPS	0.5-	2.5	0.8	1.9	32
LDGPS 1	-0.6	1.8	0.2	1.6	33
LDGPS 2	-0.7	2.3	0.1	1.8	34

Table 5
2D Results with 3 meter Height Bias (Meters) - Day 53

VIII) SUMMARY OF RESULTS AND CONCLUSIONS

The following conclusions regarding real-time DGPS accuracy can be made based upon our experience and from this research:

- The achievable accuracy of horizontal position using the DGPS method during typical SA is at the level of 3 meters in terms of rms. The final DGPS error is caused by GPS receiver noise and systematic errors. The systematic errors are orbit, tropospheric, ionospheric and residual satellite clock SA dithering errors. The influence of systematic errors on a determined position is dependent on station separation and the age of data of differential corrections.

- The DGPS accuracy deteriorates with distance due to spatial decorrelation of the certain DGPS errors. Hovever, the target three meter DGPS accuracy can be maintained for distances up to 300 kilometers, provided differential tropospheric and ionospheric corrections are used. These corrections are not presently applied to internal solutions of the investigated GPS receivers.

- The unaccounted tropospheric and ionospheric errors contribute to horizontal position error on an average of 0.7 meter per every 100 kilometers. The typical SA orbit error has practically no effect for distances under 300 kilometers. The research findings summarizing the DGPS accuracy as a function of a distance for the investigated DGPS systems are given in Fig 36.

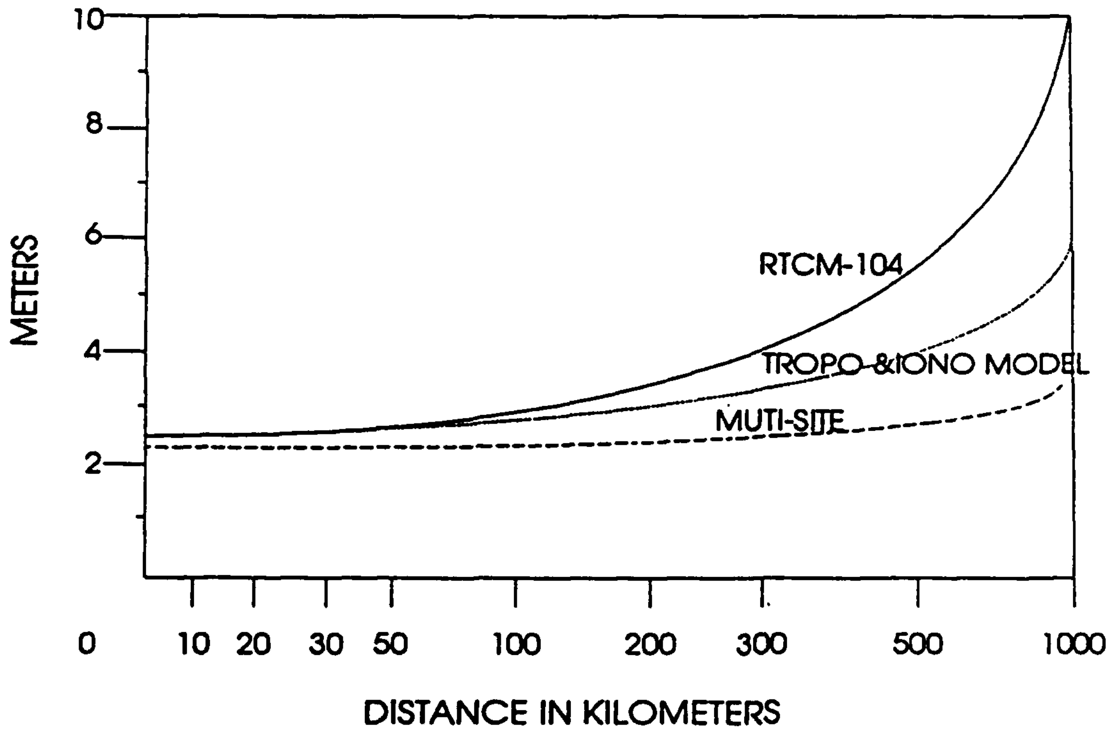

Fig 36 Horizontal DGPS Accuracy Versus Distance

- The range of operation with multiple stations can be extended to 1000 kilometers without accuracy degradation. Adding more reference stations reduces the influence of systematic errors on a determined position. In addition, use of multiple stations reduces the influence of random errors in reference part of the DGPS system. Therefore, multi-site DGPS offers more reliable and more accurate positioning than typical single reference station DGPS.

- A differential correction update rate of five seconds is sufficient to keep up with the effects of the typical Selective Availability clock dithering. Modern data links with data rates greater than 300 baud provide such an update rate of differential corrections. The residual non-linear satellite clock errors contribute to position error approximately on an average of 0.15 meter in horizontal position and 0.2 in height per every second of update rate, respectively. In general, position error due to residual SA clock dithering is non-linear and grows asymptotically. Therefore, setting a limit on the age of data of the DGPS corrections eg 30 seconds is recommended to prevent using old corrections in the case of occasional data links outages.

- Height constrained 2D mode and 3D mode provide horizontal position solutions at the same level of accuracy. However, the user ellipsoidal height that is used for height constraint in a 2D mode cannot be in error more than 3 meters. The height determined using the DGPS method in 3D mode has an accuracy of 4 to 5 meters. Height is less accurate than horizontal position components because of weaker geometry.

- Finally, it is important to conclude that DGPS accuracy is not homogeneous. There are times that DGPS position error exceeds the three meter limit. Most excursions relate to the cases of non-redundant DGPS solutions and poor geometry. The use of low PDOP masks in actual practice work eg 6 is therefore recommended. We also found that setting the mask on the rms of satellite residuals of the redundant DGPS solution helps to eliminate position outliers.

IX) REFERENCES

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